AFRL-VA-WP-TP-2003-334

VALIDATION & VERIFICATION OF INTELLIGENT AND ADAPTIVE CONTROL SYSTEMS

James M. Buffington
Vince Crum
Bruce Krogh
Clinton Plaisted
Ravi Prasanth
Prasanta Bose
Tim Johnson

OCTOBER 2003

Approved for public release; distribution is unlimited.

AIR VEHICLES DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7542

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
October 2003

2. REPORT TYPE
Conference Paper Preprint

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
VALIDATION & VERIFICATION OF INTELLIGENT AND ADAPTIVE CONTROL SYSTEMS

5a. CONTRACT NUMBER
F33615-02-C-3206

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62201F

6. AUTHOR(S)
James M. Buffington (Lockheed Martin Aeronautics Company)
Vince Crum (AFRL/VACC)
Bruce Krogh (Carnegie Mellon)
Clinton Plaisted (Lockheed Martin Missiles & Fire Control)
Ravi Prasanth (Scientific Systems)
Prasanta Bose (Lockheed Martin Missiles and Space)
Tim Johnson (General Electric)

5d. PROJECT NUMBER
2403

5e. TASK NUMBER
06

5f. WORK UNIT NUMBER
6A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lockheed Martin Aeronautics Company
P.O. Box 748
Fort Worth, TX 76101

Control Systems Development Branch (AFRL/VACC)
Carnegie Mellon University, Pittsburgh, PA
Lockheed Martin Missiles & Fire Control, Orlando, FL
Scientific Systems Company, Inc., Woburn, MA
Lockheed Martin Missiles and Space, Sunnyvale, CA
General Electric Global Research Center, Niskayuna, NY

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Vehicles Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7542

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/VACC

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-VA-WP-TP-2003-334

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
To be presented at 2nd AIAA "Unmanned Unlimited" Systems San Diego, CA, Sep. 15-18, 2003.

14. ABSTRACT
Emerging military aerospace system operational goals, such as autonomy, will require advanced safety-critical control systems consisting of unconventional requirements, system architectures, software algorithms, and hardware implementations. These emerging control systems will significantly challenge current verification and validation (V&V) processes, tools, and methods for flight certification. Ultimately, transition of advanced control systems that enable transformational military operations will be decided by affordable V&V strategies that reduce costs and compress schedules for flight certification. This paper describes a comprehensive plan and preliminary results for a study of V&V needs for emerging safety-critical control systems in the context of military aerospace vehicle flight certification.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	SAR	16	Robert R. Smith **19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-8429

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Validation & Verification of Intelligent and Adaptive Control Systems

James M. Buffington
AIAA Associate Fellow
Lockheed Martin Aeronautics Company
Fort Worth, Texas
Vince Crum
Air Force Research Laboratory
Wright-Patterson AFB, Ohio
Bruce Krogh
Carnegie Mellon University
Pittsburgh, Pennsylvania
Clinton Plaisted
Lockheed Martin Missiles & Fire Control
Orlando, Florida

Ravi Prasanth
Scientific Systems Company, Inc.
Woburn, Massachusetts
Prasanta Bose
Lockheed Martin Missiles and Space
Sunnyvale, California
Tim Johnson
General Electric Global Research Center
Niskayuna, New York

ABSTRACT

Emerging military aerospace system operational goals, such as autonomy, will require advanced safety-critical control systems consisting of unconventional requirements, system architectures, software algorithms, and hardware implementations. These emerging control systems will significantly challenge current verification and validation (V&V) processes, tools, and methods for flight certification. Ultimately, transition of advanced control systems that enable transformational military operations will be decided by affordable V&V strategies that reduce costs and compress schedules for flight certification. This paper describes a comprehensive plan and preliminary results for a study of V&V needs for emerging safety-critical control systems in the context of military aerospace vehicle flight certification.

INTRODUCTION

Flight-safety-critical system development begins with system-level requirements and ends with a validated implementation in hardware and software, as illustrated in Figure 1. Flight-safety-critical system software is any software that controls or monitors hardware whose reliability, location, or performance directly impacts the areas of probability of loss of control (PLOC), survivability, aircraft performance, and crew safety. Specific types of testing of flight-critical software are oriented to the verification of these four high-level requirements, and any software errors that remain are not flight critical.

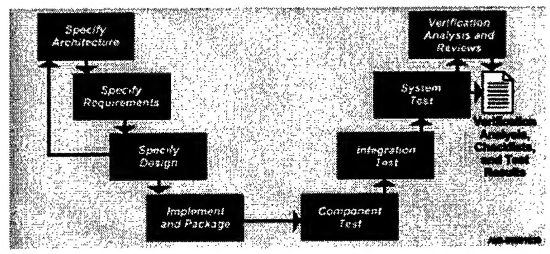


Figure 1 – Classic "V" of System Development

Safety guidelines address all aspects of software-controlled functions including hazard analysis and testing to ensure stable, predictable software behavior. Hazard analyses for safety-critical systems identify hazardous functions that are used to evaluate software requirements for adequacy in mitigating any safety risks. Hazard analysis also includes analysis of software functional descriptions, including software capability catalogs and software requirements specifications. Software causal factors are uncovered in the hazard analysis and are modeled using a functional logic diagram similar to a fault tree to graphically represent logic paths resulting in a hazard. These results are then used to recommend design provisions and tests to validate hazard controls. Prescribed safety and reliability is a significant challenge for current safety-critical software, since there is no known correlation between test coverage and hazard coverage.

Requirements, design, and test coverage and their quantification all significantly impact overall system quality, but control law software test coverage is especially significant to development costs. For current systems, control law, software implementation, and test comprise over 60% of

ASC-03-1739

total development costs (Figure 2). This percentage will be even higher using current verification and validation (V&V) strategies on emerging autonomous control systems. Although traditional certification practices have historically produced sufficiently safe and reliable systems, they will not be cost effective for next-generation autonomous control systems due to inherent size and complexity increases from added functionality.

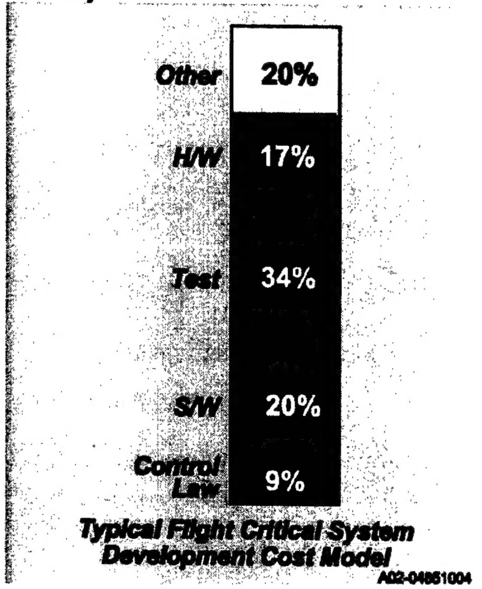


Figure 2 – System Cost Model

Next-generation unmanned air vehicles (UAVs) and unmanned space vehicles will require advanced safety-critical system attributes to enable safe autonomous operations. These emerging attributes will manifest themselves in all aspects of the system including requirements, system architectures, software algorithms, and hardware components. Future requirements may impose a reliability allocation to software, may be driven by payload or other subsystems in lieu of pilot workload, or may take on totally different forms to accommodate the safety of functionality that replaces the pilot [1]. Advanced system architectures may be highly redundant and may include integration of functions with various levels of criticality among physically distributed asynchronous processors. Software algorithms may be adaptive, learning, optimal, and predictive to provide necessary intelligence for on-line reconfiguration, decision-making, reasoning, and cooperation [2,3]. Future hardware may consist of a family of malleable processing elements to include compute cores, caches, memory structures, data paths, network interfaces, network fabrics with incremental instructions, operating system (OS), and network protocols that have the ability to reconfigure to match changing mission and scenario demands [4,5,6]. These emerging attributes may increase the size and complexity of control systems beyond the capability of current V&V practices as observed in projected source lines of code (SLOC) in unmanned reconnaissance air vehicles (URAV) and unmanned combat air vehicles (UCAV) (Figure 3).

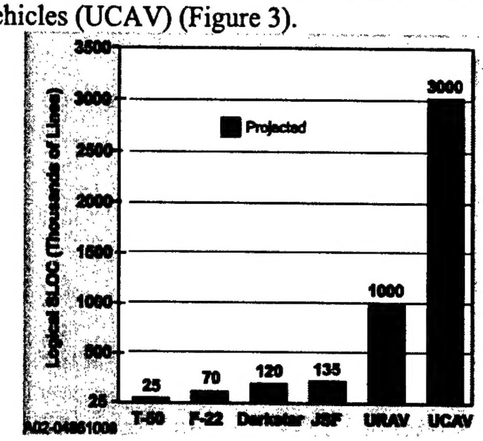


Figure 3 – Complexity Growth from Autonomy

Truly autonomous operations will require air and space vehicle safety-critical control system enhancements to achieve required safety levels without reliance on human intervention. Flight critical systems requirements assert that the occurrence of any failure condition that would prevent the continued safe flight and landing of the airplane shall be extremely improbable. This requirement is commonly specified in terms of PLOC due to failure being less than 10^{-7} for military aircraft and currently verified through semi-exhaustive quantitative and qualitative test methods.

As emerging safety-critical systems become more complex, system certification costs will increase exponentially due to a projected increase in required testing resources, such as hardware in the loop (HIL) testing labor (Figure 4).

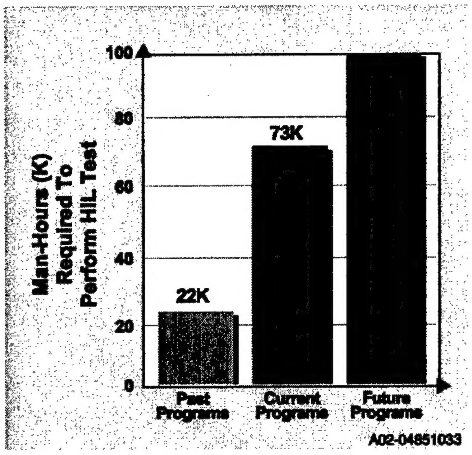


Figure 4 –Testing Hours Are Forecast to Triple

Planned test automation improvements will certainly reduce testing hours but may not sufficiently reduce them for emerging control system requirements. Rigorous verification of the PLOC requirement may not be cost effective in the presence of these system enhancements.

OBJECTIVES

The technical scope of this study is V&V of emerging safety-critical control systems for flight certification of military air and space vehicles with emphasis on autonomous vehicles. The proposed effort will focus on software V&V due to its significance to overall costs. However, model and system-level V&V will be considered due to their inherent tight interconnections. Consideration of a comprehensive view of V&V allows development of appropriate software V&V strategies that are easily transitioned into full system-level V&V for flight certification.

Our primary goal is to enable affordable development of future safety-critical systems with prescribed levels of safety and reliability. Our objective is to study, develop, and demonstrate effective V&V strategies and metrics for advanced safety-critical control system flight certification. Specific technical objectives include:

- •Classify emerging safety-critical control systems by their inherent fundamental characteristics that challenge traditional certification practices
- •Develop and demonstrate preliminary V&V strategies that focus on critical schedule and cost points within flight certification
- •Identify critical, high-payoff V&V process, tool, and method technologies for further development.

These technical objectives address relevant technical challenges that, if solved, will provide significant benefits. Specific technical challenge areas include prescribed flight safety levels, coverage and its quantification, system and software complexity, software size, scalability of solutions, failure mode coverage, learning and adaptive algorithms, and affordable development/V&V. The primary benefit of achieving these objectives is enabling cost-effective, rapid development of safe and reliable autonomous safety-critical systems.

APPROACH

Our approach centers on exploiting key interactions between V&V and flight certification of safety-critical autonomous control systems. These interactions will be studied in the five primary tasks described in the following sections.

Emerging Control System Study

The Emerging Control System Study includes tasks that address critical elements of system design such as requirements, architecture, algorithm, and implementation. Our requirements study will identify current, planned, and future capabilities of emerging control systems. The architecture study will identify current, planned, and future functional and physical architectures that accommodate the requirements. In the algorithm study, we will identify algorithms to populate the advanced architectures. The implementation study will identify software code implementations of the algorithms and hardware implementations of the software code. The primary product from this task is a study report and database that will capture relevant aspects of representative emerging safety-critical control system design across the industry. Subsequent Control Characteristics and V&V Needs Study and Innovative Flight Certification Strategies Development tasks will assess and compare the data from this task.

Control Characteristics and V&V Needs Study

The objective of the Control Characteristics and V&V Needs Study is to identify critical V&V process, tool, and method technology needs for guiding the development of innovative flight

certification strategies that significantly reduce certification costs and schedule. This task consists of an emerging control system characterization, a flight certification process review and deficiencies assessment, and a needs assessment for V&V tools and methods. Our approach is to characterize the database of emerging safety-critical control systems according to structures, features, and attributes that have significant impact to flight-safety certification cost and schedule. We plan to review current flight certification practices, including design, analysis, test, and V&V, to identify process challenges and deficiencies for certification of emerging autonomous control systems. We also plan to assess V&V tool and method needs for improving flight certification cost, flight certification effort, and accuracy of emerging control system safety, reliability, and behavior. Our characteristics review and needs assessment approach is based on impact to flight certification cost and schedule and feasibility of correcting critical needs that relate to a variety of characteristics. The primary product of this task is a Control Characteristics and V&V Needs Study report that will guide the development of innovative flight certification strategies.

Emerging autonomous control systems have certain characteristics and attributes that challenge current and planned V&V processes, tools, and methods. Challenging algorithm functional attributes may include adaptation, intelligence or learning, optimization, prediction, reasoning, decision-making, and cooperation. Challenging system architecture structural features may include function integration and physical distribution that require synchronization. However, these system attributes may be further categorized by fundamental mathematical properties that better characterize V&V challenges. For example, non-determinism of intelligent and reasoning algorithms is what truly challenges current V&V practices.

Our needs assessment approach leverages an organizational framework that links control system characteristics directly to V&V needs through fundamental mathematical properties (Figure 5). This innovative approach enables a traceable, focused identification of the most critical flight certification process, tool, and method deficiencies based on a solid mathematical foundation. Application and algorithm classes will be established and relevance/importance of properties will be identified for each class and each development phase. This study will map technologies/techniques to relevance areas, identifying high-payoff (exploitation) areas and guiding development of new techniques and technologies.

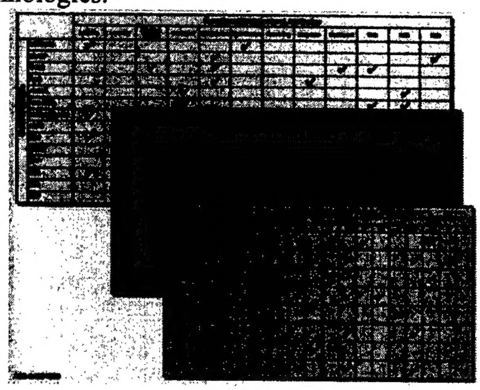


Figure 5 – Assessment Framework

Our control characterization approach is to focus on requirements and algorithmic characteristics while considering their software implementation within hardware system architectures. We will utilize the database of emerging safety-critical control systems to identify critical requirements specification, algorithm functional, system architectural, and implementation characteristics.

We will first identify critical challenging requirements attributes and how these evolve into functional and architectural attributes such as adaptation, intelligence, decentralized, and others to be determined. These functional attributes will then be reviewed to identify and precisely define critical challenging mathematical properties such as non-determinism, non-stationary, and others to be determined. These mathematical properties will be the basis used for the needs assessment of flight certification V&V processes, tools, and methods. We will also identify metrics (e.g. McCabe software metrics [7]) and tests for determining existence of the emerging control characteristics.

There are well-established flight certification processes that have evolved over time to provide highly safe and reliable flight systems. However, cost effectiveness of these processes needs to be improved for next-generation systems. We will review the current flight certification processes considering the emerging control system

characteristics and based on an innovative process representation that allows us to identify criticality of current V&V process deficiencies. A primary product of this task is a representative model of flight control system development using current practices, processes, methods, and tools.

Our approach, notionally depicted in Figure 6, is based on determining the most critical cost and schedule impact points within current processes. This approach allows quick focus on the most relevant tools, methods, and process areas that will significantly impact cost and schedule. We will first review flight certification, software development, and V&V process flow diagrams. Then these process elements will be mapped to a notional schedule. For each scheduled activity, cost estimates will be established based on required manpower and resources. This will provide a critical path, time-phased, resource-loaded representation of system development for evaluation. We will then assess the impact of the emerging control characteristics on current state-of-the-art system development using the representative development model. This will assist in identification of critical needs that have most favorable impact on emerging control system cost and schedule.

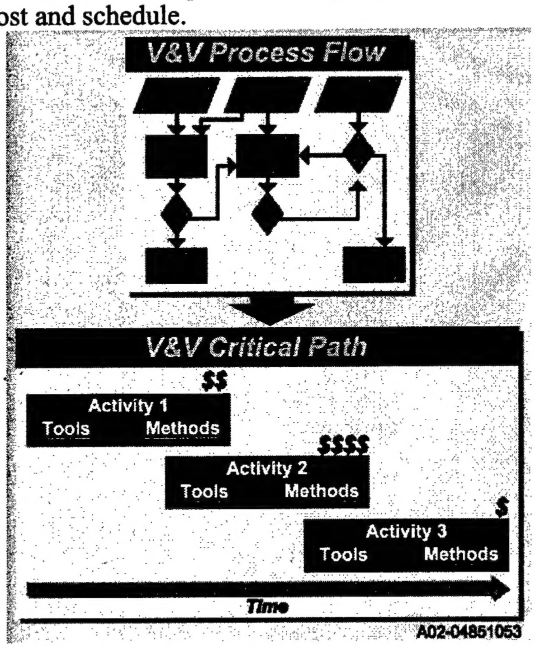


Figure 6 – Critical Path Process Analysis

Once we have identified deficiencies in current practices applied to emerging control system characterisitics, we will survey technologies that are being developed, and map the most applicable tools and methods to the activities in our representative development model. We will assess a comprehensive set of V&V processes, tools, and methods from our team's database and the existing literature at large based on objective metrics established during the study. Assessment metrics may include flight certification cost, flight certification effort, flight certification time, accuracy of advanced system behavior, and others determined during the program. The assessment will identify deficiencies and needs that are traceable to the specific emerging control system within our structured framework (Figure 5). This assessment will include a detailed description of how and why current V&V techniques are not suitable to emerging advanced flight-safety-critical systems. This assessment will be the basis for the identification of V&V needs.

Flight Certification Strategies Development

The objective of the Innovative Flight Certification Strategies Development task is to develop strategies that most favorably impact cost reduction and schedule compression for flight certification. For example, system development schedules may be significantly compressed by formalized time phasing alone in which testing is started earlier in the development cycle (Figure 7). Additional cost and schedule reductions are possible by reducing V&V testing time with improved processes, tools, and methods.

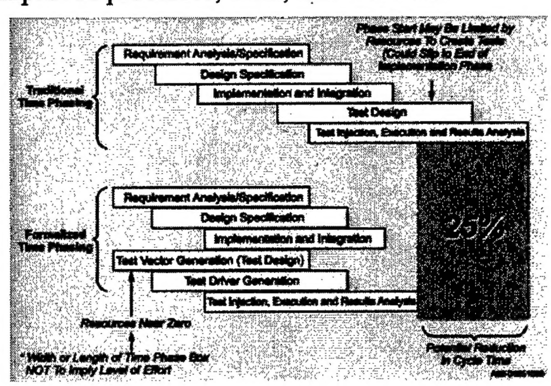


Figure 7 – Process Improvements

This task will include sub-tasks that address development of requirements, refinement of flight certification processes, development of V&V methods, and development of representative systems. We will derive requirements needed to improve the deficiencies identified in the design,

analysis, test, V&V, and implementation development phases. We will refine current flight certification processes and/or create innovative certification strategies that address these requirements. Feasible V&V strategies that improve flight safety while reducing software development and life-cycle costs (LCC) will be developed. We will also develop representative system models and software implementations that capture critical attributes and characteristics of advanced safety-critical systems to be used in the evaluation of the innovative flight certification strategies and V&V methods. The primary products of this task are requirements for improved flight certification, preliminary flight certification strategies and concepts, and representative safety-critical systems that may be used to evaluate the certification strategies.

Our innovative technical approach to this task centers on a three-view perspective of flight-critical systems (Figure 8). All three orthogonal views (functional, object / entity / data, and dynamic / control / behavior) are present in the system simultaneously, and must be comprehensively verified and validated for flight certification. Our approach will focus on developing innovative certification strategies that address these three system views through all system development phases.

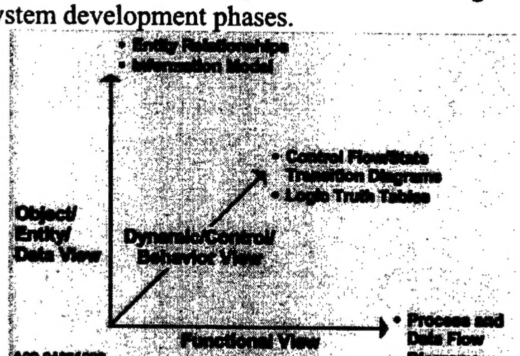


Figure 8 –Safety-Critical System Views

Our approach is to investigate V&V process, tool, method, and technology that impact all phases of system development. Early development phase activities focus on the initial translation of requirements into concrete design artifacts such as model-based design environments, formal specification techniques [8], and advanced V&V-aware design techniques [9,10]. Mid-phase development activities typically include the expression of a design into executable software and preliminary testing and verification such as control analysis [11,12], software implementation [13], and formal V&V [14,15,16,17]. Late development phase activities focus on test and review for certification and may be impacted by improvements to automated test [18] and process-based certification.

Proof of Concept

Our efficient proof-of-concept approach will enable a focused preliminary feasibility assessment of the most promising innovative flight certification strategies. This task consists of evaluation metrics definition, trade study comparison of concepts, and a simple component demonstration. We will define the most critical metrics that capture efficiency improvements in V&V of safety-critical systems for flight certification, such as testing hours and coverage. We will compare strategies against these metrics using analysis results which are qualitatively entered into established trade tools. The most promising strategies will be demonstrated within a representative flight certification V&V cycle.

We will define critical metrics for V&V methods and flight certification strategies proof of concept evaluation. The metrics will consider all aspects of development including design, analysis, test, V&V, including control performance verification and end software production. Baseline critical metrics to be considered include feasibility, flight safety, software development cost, LCC, flight certification cost, flight certification effort, and accuracy of advanced system behavior. Other potential metrics to be considered include schedulability, resource utilization, quality of service, test coverage, reachability, touch labor reduction, product size (SLOC), design cycle time, software defect density, reliability, maintainability, and retrofit.

Our strategy and concept comparison will start with an appropriate mixture of theoretical, simulation, and experimental analysis to cover all aspects of evaluation. The concepts will be qualitatively assessed against the critical metrics based on the analysis results to illustrate the initial safety-critical application feasibility of the concepts. The assessment will include accommodation of any known or predicted issues

concerning the methods for flight certification of emerging flight critical software. The qualitative assessment will be used in existing trade tools for the final comparison ranking. The ranking results will be used to identify the most promising concepts for demonstration.

Although focused on software V&V, our component demonstration will be based on a representation of the actual flight certification cycle to capture relevant issues within the ultimate system-level V&V application (Figure 9).

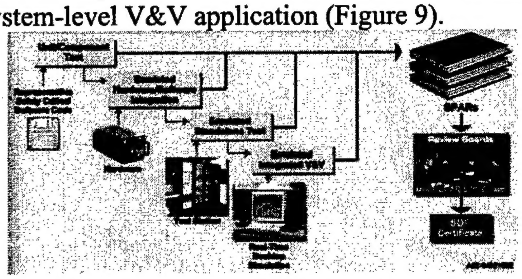


Figure 9 – Concept Demonstration

We will demonstrate the most promising V&V techniques and certification strategies within the context of component level/unit-test of the representative future safety-critical systems. This demonstration will show applicability toward an ultimate application in flight certification of future intelligent and adaptive control systems. This demonstration will be developed to mimic a real safety-of-flight (SOF) board. This mock SOF board consisting of aircraft program personnel will be assembled to demonstrate the innovative flight certification strategies.

Technology Maturation Planning

For the technology development planning and reporting task, our objective is to develop a technology investment plan based on a prioritized list of preferred innovative V&V technologies. The prioritized technology list will be developed using the proof-of-concept evaluation results.

We will complete technology roadmaps for promising V&V technologies based on well-established team methodologies and fundamental principles and approaches in the literature [19]. Using the risk waterfall template shown in Figure 10, we will complete a technology maturation plan for each of the emerging technologies identified during the program. We will provide detailed information and roadmaps for the continued investment and development of innovative V&V technologies for the purpose of making the technologies ready for the certification of emerging advanced control systems.

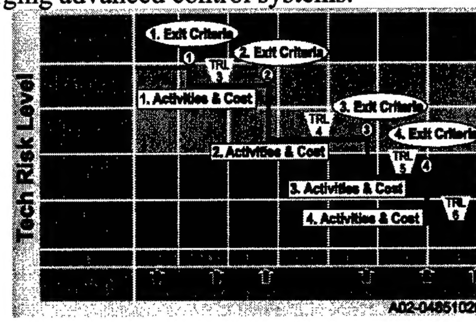


Figure 10 – Risk Waterfall Assessments

STATUS

The study schedule is illustrated in Figure 11. At the time of submission, we had completed the Emerging Control System Study task and begun the Control Characterization and V&V Needs Study task. We have also compressed the schedule to complete the entire program by September 2004.

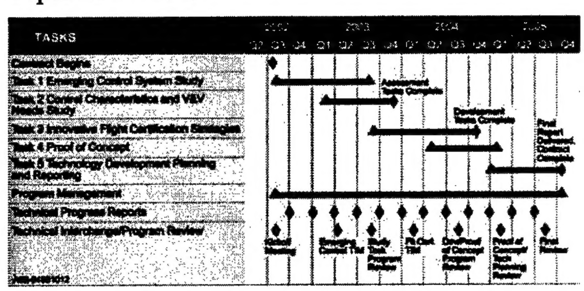


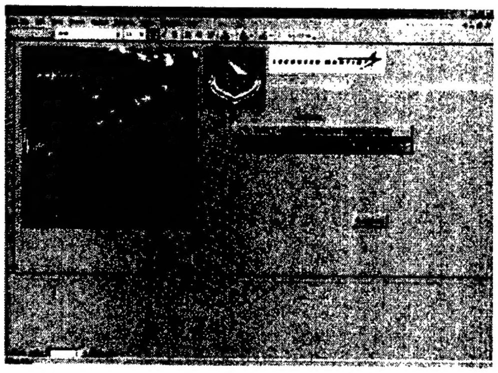
Figure 11 – Study Schedule

Emerging Control System Study

The main products from the Emerging Control System Study task are a database of control system development projects and detailed documentation from ten representative Emerging Control Systems identified from this database. We have made significant progress in developing these products. We have defined the Emerging Control System data collection format and developed a Microsoft Access tool for collecting the data (Figure 12).

Each team member has reviewed their past, current, planned, and future programs and input summary data into the database tool. We have populated the database with data from more than 40 projects and programs. We have begun to study and analyze the summary data in preparation for a down-select to a subset of programs that will

define the representative Emerging Control Systems that will be carried through the remainder of the study.



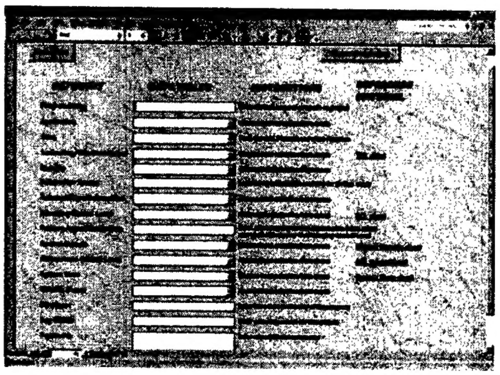


Figure 12 – Control System Database

Each database project has been scored based on an assessment of primary and secondary criteria. The primary criteria are advanced or emerging control level and availability of detailed data for further evaluation. The emerging control level is a qualitative criterion that we defined that captures whether a project is behind (low), within (medium), or beyond (high) the current state-of-the-art. Secondary evaluation criteria included diversity among control domain and application area to widen relevance of study results. In the context of this study, control domain captures the area of control (i.e. inner-loop, guidance, etc.) and application domain captures the area of product type for which the control is applied (e.g. military aircraft, military spacecraft, etc.). From this assessment and scoring, the projects in Table 1 were identified as our preliminary representative emerging control systems.

Table 1 – Emerging Control Systems (ECS)

ECS PROJECT	DESCRIPTION
AIMSAFE / RESTORE	Integrated Management, Adaptive Control
ICARUS	Intelligent Autonomy
LOCAAS	Autonomous Control
Enhanced GNC Algorithms	Dynamic Programming Optimization
XACT	Adaptive Failure Management
Software Enabled Control	Optimal Trajectory Generation
EDCS F-16 Autopilot	Outer Loop Hybrid Control
Engine Control Cutoff Mode	Nonlinear Hybrid Control
Intelligent Engine Control	Intelligent Failure Management
Intelligent Maintenance Advisor for Turbine Engines	Model-based Health Management
Formation Flying Spacecraft	Multi-vehicle Control

<u>Control Characteristics and V&V Needs Study</u>

We have identified a preliminary set of emerging control characteristics within the Control Characterization and V&V Needs Study Task. We have also constructed a preliminary representative flight control system development plan. This plan was developed by utilizing existing engineering processes and actual product program development plans from industry team members. This plan represents a traditional development process with qualitative schedule and cost assessments included. Our plan is to assess the impact of Emerging Control System characteristics on this system development plan. The control characteristic impacts will be prioritized to address V&V needs based on schedule and cost criticality within this representative development plan.

<u>CONCLUSIONS</u>

We have developed a study plan to identify V&V technologies that significantly reduce costs and compress schedules of military aerospace

vehicle flight certification. Our innovative approach is based on a comprehensive system development and operational perspective and sound system engineering principles. We have compiled a database from which the industry at large may draw upon and identified a preliminary set of representative emerging control systems which will be utilized for preliminary V&V technology development and technology maturation planning.

ACKNOWLEDGEMENTS

This work is being funded by the Flight Control Division in the Air Vehicles Directorate at the Air Force Research Laboratory under contract F33615-02-C-3206.

REFERENCES

1. Clough B., "Autonomous UAV Control System Safety – What Should It Be, How Do We Reach It, And What Should We Call It?," 2000 NAECON.
2. Eberhardt R.L. and Ward D. G., "Indirect Adaptive Flight Control of a Tailless Fighter Aircraft", 1999 AIAA Guidance, Navigation, and Control Conference, Portland, OR, Paper 99-4042.
3. Niestroy M.A. and Eberhardt R.L., "Control Upset Prevention and Recovery for Enhanced Aviation Safety", 2000 Digital Avionics Systems Conference, Philadelphia, PA, Paper 202.
4. Renau J., Tuck J., Liu W., and Torrellas J., "Morphable Multithreaded Memory Tiles (M3T) Architecture," University of Illinois UIUC-CS Technical Report, September 2002
5. Keckler S. W., Burger D., Moore C. R., Nagarajan R., Sankaralingam K., Agarwal V., Hrishikesh M. S, Ranganathan N., and Shivakumar P., "A Wire-Delay Scalable Microprocessor Architecture for High Performance Systems", IEEE International Solid-State Circuits Conference, February 2003.
6. Taylor M. B., Lee W., Amarasinghe S., and Agarwal A., "Scalar Operand Networks: On-chip Interconnect for ILP in Partitioned Architectures." Proceedings of the International Symposium on High Performance Computer Architecture, February 2003.
7. Watson A. H. and McCabe T. J., "Structured Testing: A Testing Methodology Using the Cyclomatic Complexity Metric." National Institute of Standards and Technology, NIST Special Publication 500-235, August 1996.
8. Gluch D. and Weinstock, C., "Model-Based Verification: A Technology for Dependable System Upgrade," CMU/SEI-98-TR-009, ADA 354756.
9. Seto D., Krogh B., Sha L., Cury J., Chutinan A., and Biswas A., "Safe Online Control Upgrades with the Simplex Architecture – A Hybrid System," Hybrid Systems and Autonomous Control Workshop.
10. Prasanth R. K., , Boskovic J. D., and Mehra R. K., "Development of Assurance Techniques for High-Confidence Flight Software Design for Autonomous Unmanned Air Vehicles," DARPA Phase I SBIR final report, SSCI Report No:1311, 2001.
11. Boskovic J. D. and Mehra R. K., "Computer Simulation Analysis for Reconfigurable Flight Control Design," 2002 AIAA Modeling and Simulation Conference and Exhibit, Monterey, California, August 2002, AIAA-2002-4787.
12. Davis M. H. A., Markov Models and Optimization, Monographs on Statistics and Applied Probability, Vol. 49, Chapman and Hill, New York, 1993.
13. Rimvall C.M., Spang H.A. III, Farrell, J.A., Radecki M., and Idelchik M., "An open architecture for automatic code generation using the BEACON CACE environment," IEEE/IFAC Joint Symposium on Computer-Aided Control System Design, p. 315-320, 1994.
14. Henzinger T.A.; Pei-Hsin Ho; Wong-Toi, "HYTECH: a model checker for hybrid systems," International Journal on Software Tools for Technology Transfer, vol.1, no.1-2 p. 110-22, Dec. 1997.
15. McMillan, "Symbolic model checking: an approach to the state space explosion problem," Carnegie Mellon University, School of Computer Science, Ph. D. Thesis, 1992.

16. Silva I. and Krogh B., "Formal verification of hybrid systems using CheckMate: a case study," 2000 American Control Conference, Chicago, June 2000.

17. Prasanth R. K., , Boskovic J. D., and Mehra R. K., "Mixed integer/LMI approach to low level path planning," Proceedings of the American Control Conference, May 2002.

18. Blackburn M., Busser R., Nauman A., "Removing Requirement Defects and Automating Test," 2001 Software Productivity Consortium.

19. Garcia M. L and Bray O. H., "Fundamentals of Technology Roadmapping," Sandia National Laboratories Unlimited Release Document, SAND97-0665.